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FINAL REPORT

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STRUCTURE AND MIXING IN TURBULENT SHEAR FLOWS

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SUMMARY

The research problems in turbulent mixing studied under this contract were the following:

1. Supersonic turbulent mixing layers,
2. Transverse jets,
3. Burning free jets,
4. Theoretical models.

Significant results obtained are briefly summarized in the following Discussion. Complete descriptions of the research and of the results are contained in the references cited.

DISCUSSION

Supersonic Turbulent Mixing Layers

The relationships of large structures and growth rate to convective Mach number M_c were further investigated. Measurements of large-scale structure convective velocity, by double-exposure spark Schlieren photography, showed that entrainment may be unexpectedly asymmetric at high values of M_c, where compressibility has a large reducing effect on growth rate. The investigations are reported and described in the following publications and contributions.

Publications in refereed journals

D. Papamoschou and A. Roshko 1988 Observations of supersonic free shear layers. Sadhana, J. Indian Academy of Sciences, **12**, Feb., 1-14.

D. Papamoschou and A. Roshko, 1988 "The turbulent compressible shear layer: An experimental study," J. Fluid Mechanics **197**, 453-477.

D. Papamoschou, 1988 "Diffuser performance of two-stream supersonic wind tunnels," accepted for publication in the *AIAA Journal*.

D. Papamoschou, 1988 "A two-spark schlieren system for very-high velocity measurements," submitted for publication to *Experiments in Fluids*.

Invited and contributed reports

D. Papamoschou, "Outstanding issues in the area of compressible mixing," Invited Lecture at the *International Workshop on the Physics of Compressible Mixing*, Princeton University, October 1988.

D. Papamoschou, "Structure of the Compressible Turbulent Shear Layer," AIAA 89-0126 presented at the *AIAA 27th Aerospace Sciences Meeting*, January, 1989.

Transverse Jets

New insights were obtained into the large vortical structure in turbulent jets injected into a uniform cross flow. A train of trailing vortices, which are quite intense under some conditions, has been discovered in the wake of such a transverse jet. This is reminiscent of the vortex street behind a solid cylinder but has a very different genesis. It is not a result of "vortex shedding" off the cylindrical jet but originates in the boundary layer of the wall from which the jet issues, after a complex process of unsteady separation and convection in the field of the jet.

Publications

T. Fric and A. Roshko 1988 "Views of the transverse jet near field," Physics of Fluids, **31**, no. 9, Sept., 2390.

T. Fric and A. Roshko 1988 "Structure in the near field of the transverse jet". Submitted to the Symposium on Turbulent Shear Flows, Stanford University, 21-23 August, 1989.

Burning Free Jets

A mechanism has been proposed in which the stability of a lifted turbulent jet flame is determined by the strain between large-scale structures in the jet flow field. A model has been developed using simple chemistry and large-scale flow parameters which provides a linear relationship between the liftoff height and the jet exit velocity for a simple non-coflowing axisymmetric jet flame. This model agrees well with our experimentally measured liftoff heights for a variety of pure fuels. The fluctuations in liftoff height measured in the present study are consistent with flame propagation from one large-scale structure to its upstream neighbor, and provide evidence that large-scale dynamics determine the stabilization condition.

Contributed Reports

Richard C. Miake-Lye and Jay A. Hammer 1988 Lifted turbulent jet flames; a stability criterion based on the jet large-scale structure. Presented at the 22nd International Symposium on Combustion, 14-19 August, Seattle, Washington.

Theoretical Models

A model of turbulent mixing and chemical reaction product in turbulent jets and mixing layers has been formulated. It is based on the concept that molecular mixing occurs during and at the end of cascades from the largest to the smallest scales in the flow. Molecular transport comes into play in the "flame sheets" that form between reactant streams, and it is in these effects that the model predictions differ significantly from models based on mean-flow gradient diffusion concepts. It explains the experimentally observed effects of Reynolds number, Schmidt number and Damköhler number. It is found that Reynolds number influences the effective reaction rate for Re as high as 10^6 and that the reaction rate becomes mixing limited for values of the Damköhler number, based on time of flight to the measuring station and the overall reaction time, of about 40. The model contains two physical constants, with clear physical meaning, that are determined from experiment. The crucial role of Taylor scale (in addition to Kolmogoraff scale) is demonstrated.

Contributed Reports

J.E. Broadwell and M.G. Mungal 1988 "Molecular mixing and chemical reactions in turbulent shear layers." Presented at the 22nd International Symposium on Combustion, 14-19 August, Seattle, Washington.

J.E. Broadwell 1988 "A model for reactions in turbulent jets: effects of Reynolds, Schmidt, and Damköhler numbers." In: *Proceedings of the July 1987 U.S.-France Workshop*, Turbulent Reactive Flows, Vol. I, Springer-Verlag.

J.E. Broadwell 1988 "Molecular mixing and chemical reactions in turbulent shear flows." In: *Disorder and Mixing*, E. Guyon, Y. Pomeau, E. Charlaix, J.-P. Nadal, eds., Kluwer Publishing, in press.

Other Publications and Reports

Cimbala, J., Nagib, H. and Roshko, A. 1985 "Large Structure in the Far Wakes of Two-Dimensional Bluff Bodies". J. Fluid Mechanics **190**, 265-298.

Bernal, L.P. and Roshko, A. 1986 Streamwise vortex structure in plane mixing layers". J. Fluid Mechanics **170**, 499-525.

Bernal, L.P. 1988 The statistics of the organized vortical structure in turbulent mixing layers. Physics of Fluids **31**, no. 9, September, 2533-2543.